Measurement of the W and Top Masses in CDF

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On Behalf Of The CDF Collaboration

SUSY06 - UCIrvine

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What W & top masses got to do with SUSY ?

Top & W masses are fundamental parameters of the SM

Measured to 0.014% at $Q^2=m_Z^2$

$$M_W^2 = \frac{\pi\alpha_{em}}{\sqrt{2}G_F \sin^2\theta_W (1-\Delta r)}$$

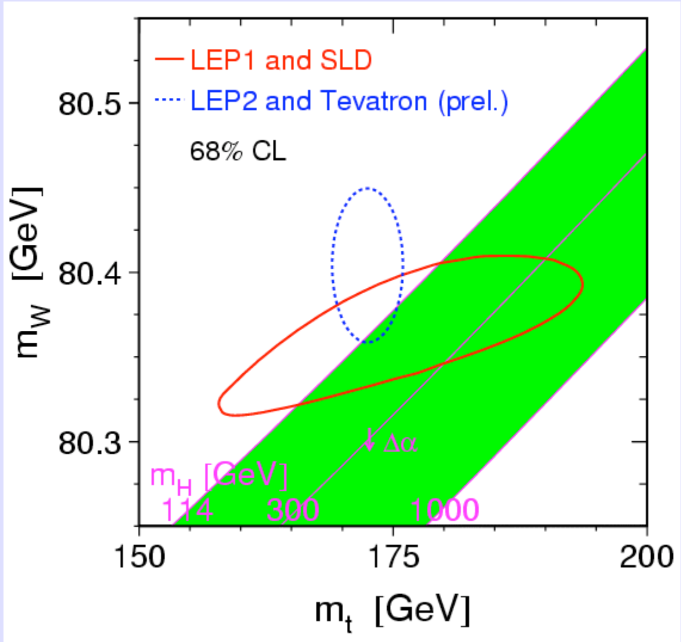
Measured to 0.0009% with muon lifetime

Measured to 0.004% at LEP

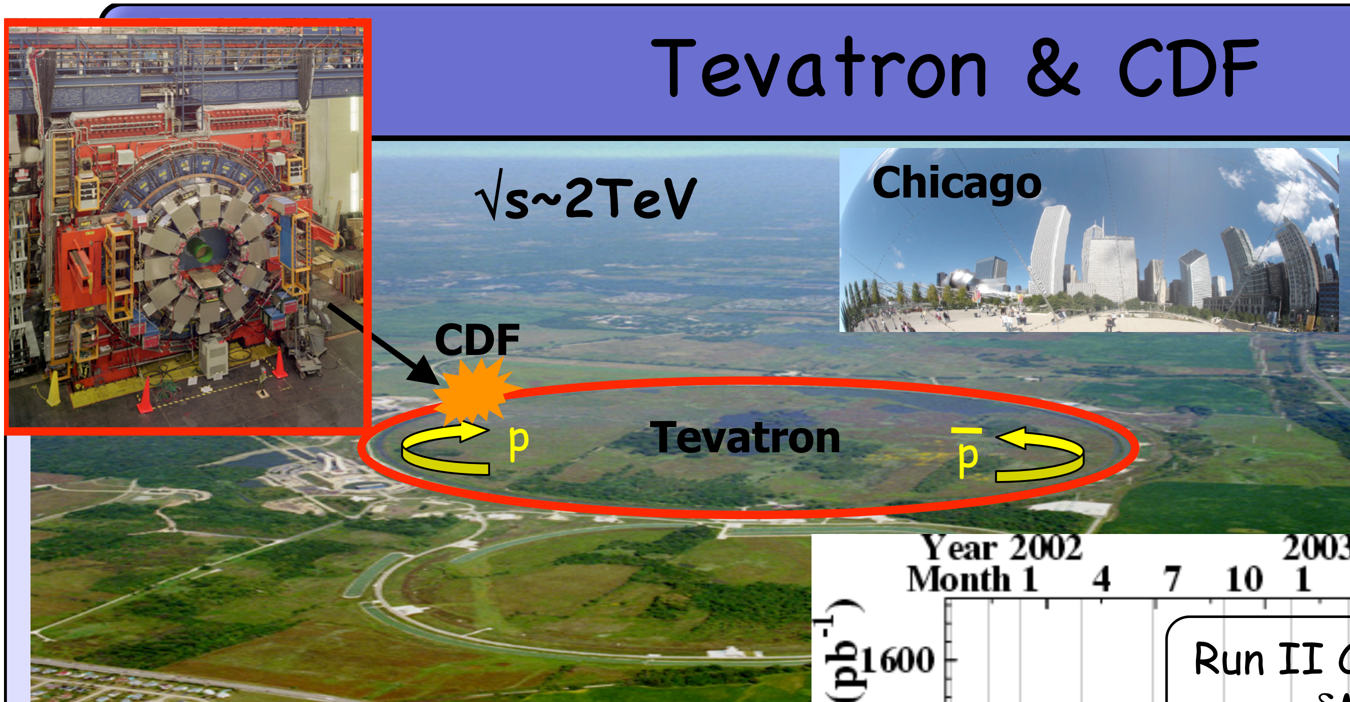
Radiative corrections dominated by top & Higgs (0.67% correction)

$\Delta m_W \propto m_t^2$ $\qquad$ $\Delta m_W \propto \ln m_H$

- Consistency check of SM parameters
- Precision measurements of M_{top} & M_W allow prediction of M_{Higgs}
- Constraint on M_{Higgs} can point to physics BSM
- Constraint on SUSY models

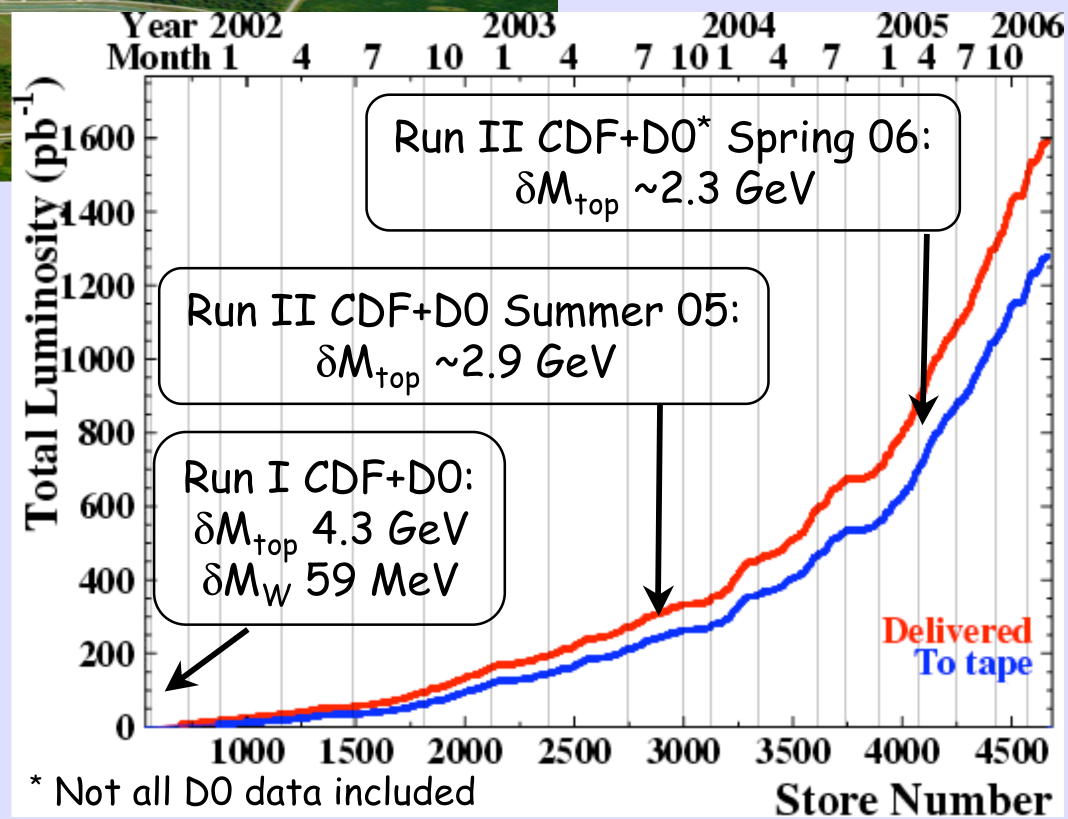


Tevatron & CDF



Recorded ~1.3 fb^{-1}
Peak Luminosity
~1.8E32 $cm^{-2}s^{-1}$

<u>CDF: Multi-purpose detector:</u>
Excellent tracker w/Si
Calorimeters
Muon chambers



Goal in TDR with 2fb^{-1}

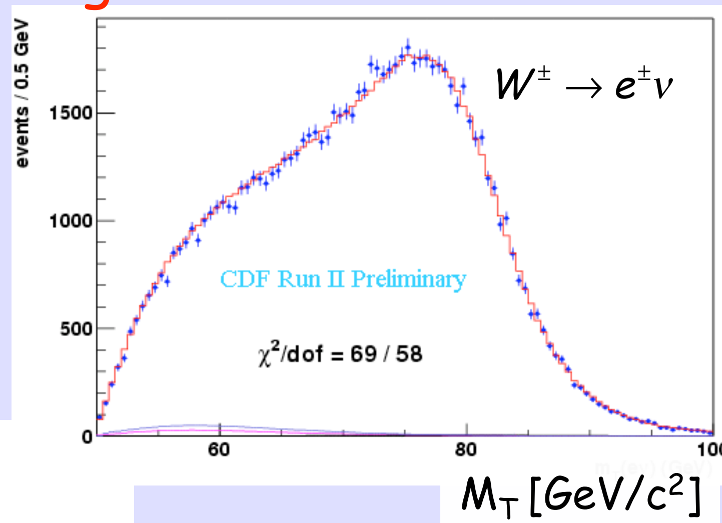
$$\delta M_{top} = 3GeV / c^2$$

$$\delta M_W = 40MeV / c^2$$

W Transverse Mass

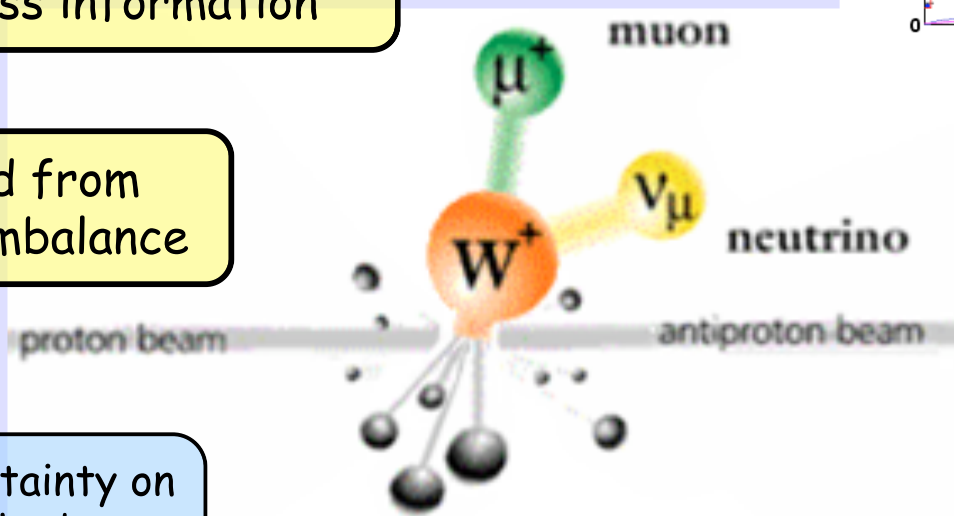
Measurement of the W mass is done by fitting the Jacobian edge of the W transverse mass:

$$M_T = \sqrt{2p_T^l p_T^\nu (1 - \cos\phi_{l\nu})}$$



Calibrate lepton p_T ~0.01%.
Bulk of mass information

p_T^ν inferred from measured E imbalance



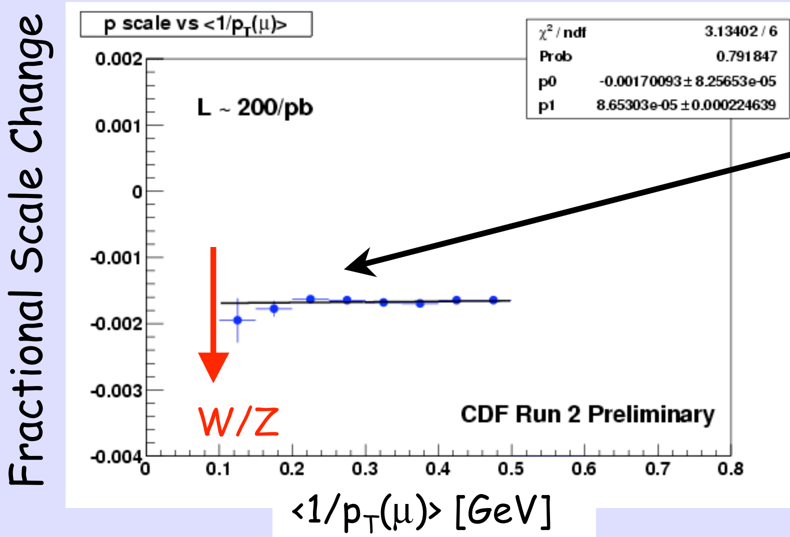
W production model:
- Rapidity (PDF's)
- p_T (QCD radiation)

Dominant uncertainty on p_T^ν come from hadrons recoiling against W

Use Z decays to model boson p_T distribution, detector response to hadronic recoil energy

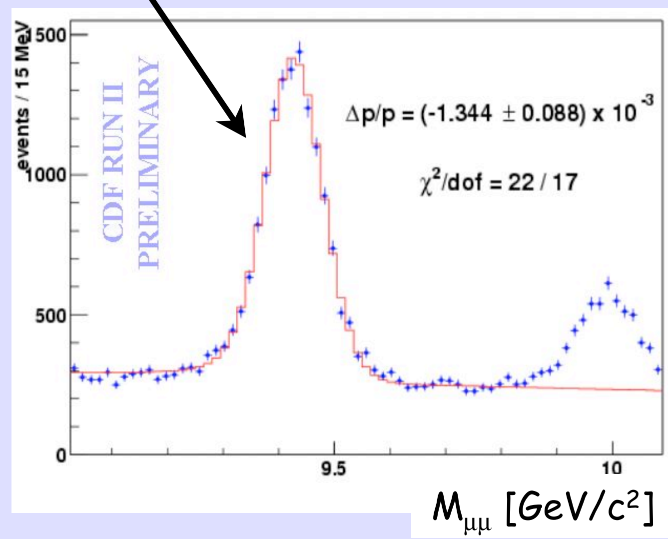
Muon Momentum Calibration

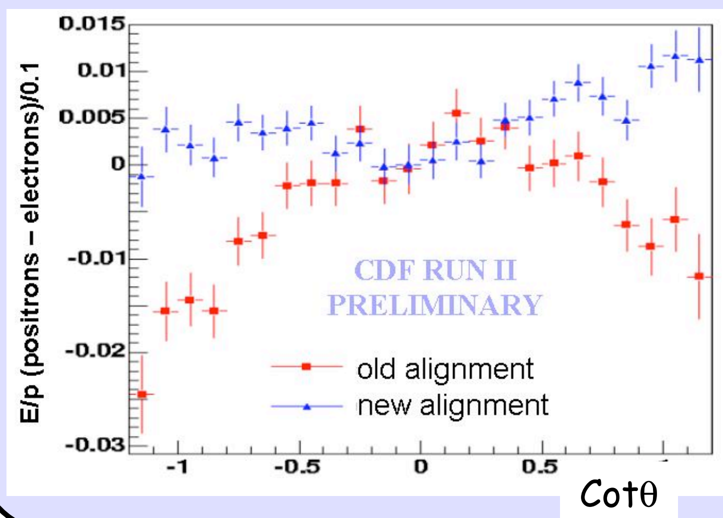
Set momentum scale using J/ψ (Υ)$\rightarrow\mu^+\mu^-$. Checked using $Z\rightarrow\mu^+\mu^-$



After corrections for energy loss in material, scale dependence on p_T is small $\rightarrow$ reliably extrapolate to W/Z scale.

Υ mass constrains tracker non-linearity and test prompt track fit





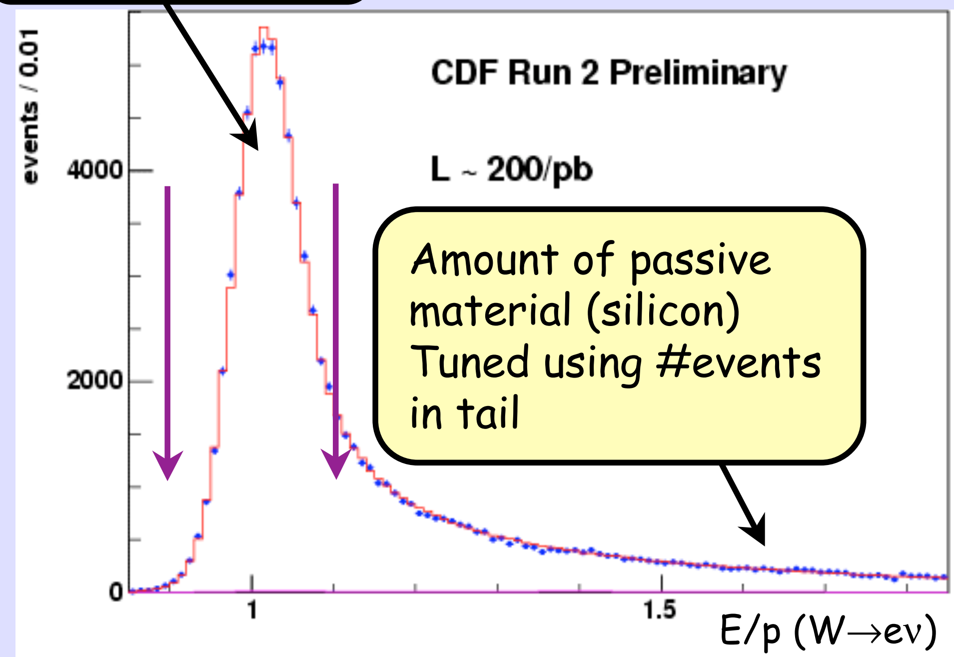
Momentum scale determined to 3 parts per 10,000

$$\delta_{M_W} \sim 15\ (scale) + 20\ (aligment) = 25 MeV$$

Electron Energy Calibration

- Use calibrated track to set calorimeter electromagnetic scale
  - E/p peak in $W^{\pm} \to e^{\pm}\nu$ events determines energy scale.

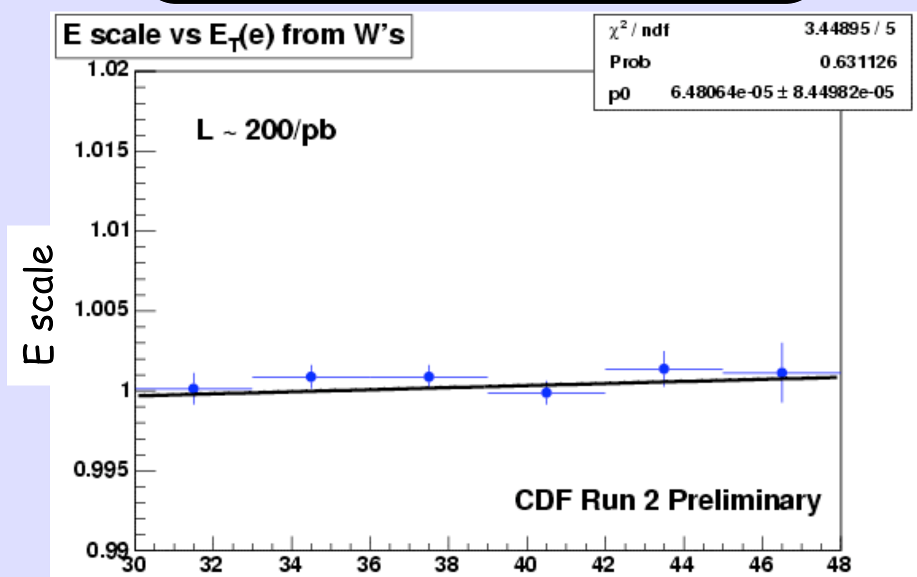
Fit scale in peak region



Amount of passive material (silicon) Tuned using #events in tail

E/p ($W \to e\nu$)

Measure calorimeter non-linearity using E/p distribution in bin of E_T



E_T^e [GeV]

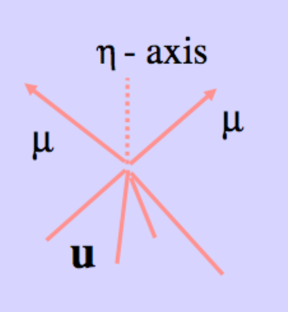
$$\delta_{M_W} \sim 35\ (stat) + 55\ (material) + 25\ (non\text{-}lin) = 70 MeV$$

Hadronic Recoil Model

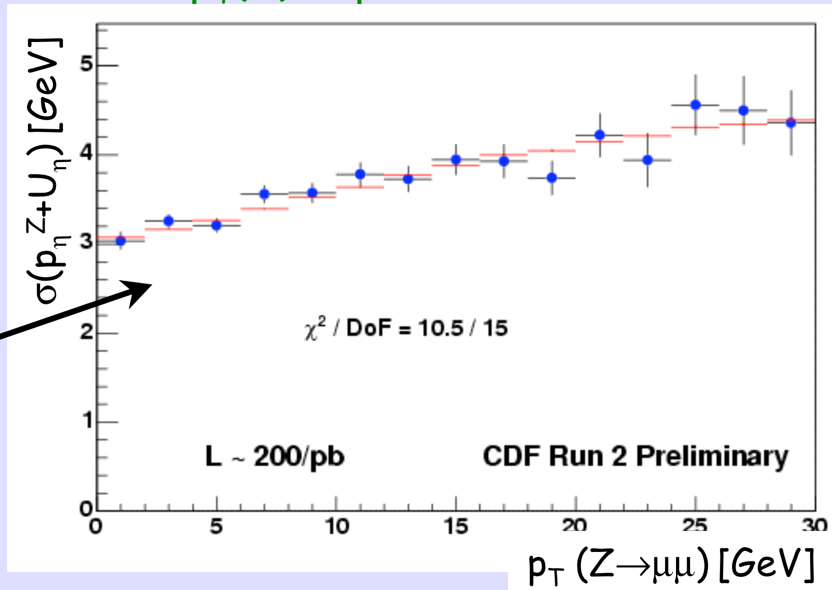
- Parametrize hadronic response $R = U_{meas} / U_{true}$
- Resolution model combines terms from
  - Underlying event: $\delta_{M_W} = 37 MeV$
    - Independent of recoil but luminosity dependent
    - Resolution model tuned on min-bias events
  - Jet resolution $\delta_{M_W} = 20 MeV$
    - Accounts for resolution $p_T(Z)$ dependence

U_{true} given by $P_T(Z)$
$\delta_{M_W} = 20 MeV$

Tuned parameters using $Z \to \mu^+\mu^-$



Width of U distribution projected along angular bisector of leptons vs $P_T(Z)$



Resolution as a function $\sqrt{p_T(Z)}$

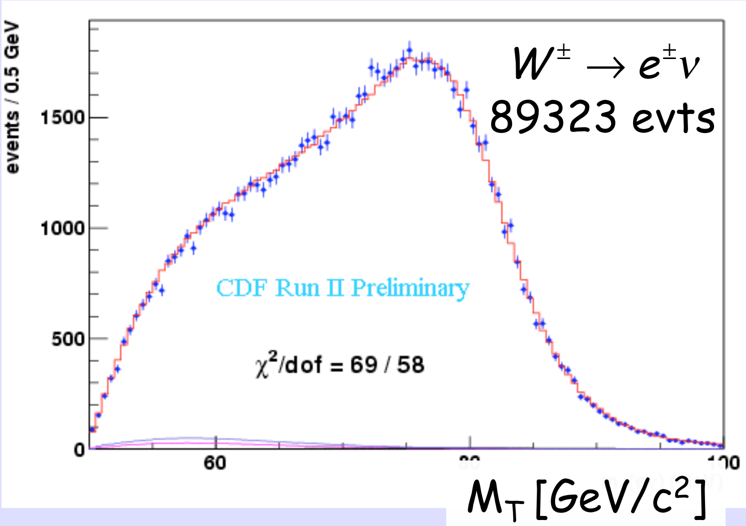
$\delta_{M_W} \sim 50 MeV$

W Production & Decay Model

- W/Z production: $\delta_{M_W} = 15 MeV$
  - 2 ingredients: W p_T, fractional momenta of u & d quarks inside the proton (determine p_Z^W, which affects M_T)
  - Embodied in PDF's (CTEQ & MRST)
- QCD corrections to W/Z production: $\delta_{M_W} = 13 MeV$
  - Model boson p_T using event generator (RESBOS) with NLL calculation and non-pertubative parameters constraint with Run I Z p_T data.
- QED corrections to W/Z decay: $\delta_{M_W} = 15 - 20 MeV$
  - Simulate radiation of final state photon according to energy and spatial distribution from NLO event generator (WGRAD)

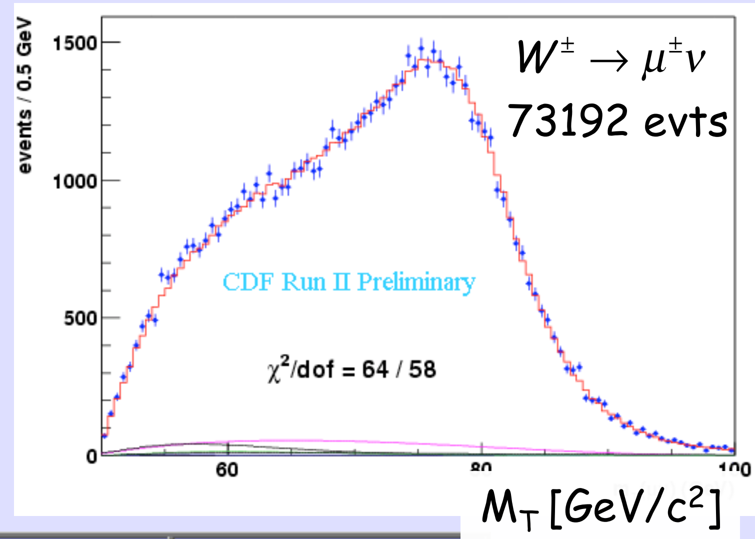
$\delta_{M_W} \sim 27 MeV$

W Mass Fit & Systematics



Fits blinded with additive offset

Good χ^2 for fit



Run Ib:80 pb^{-1}

($\sqrt{s}$=1.8TeV)

Run II: 200 pb^{-1}

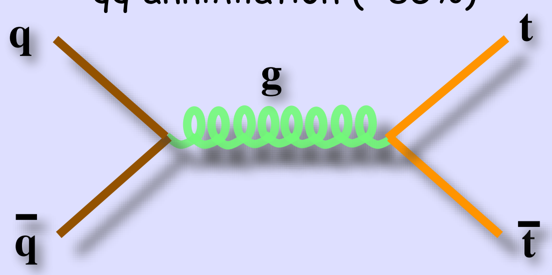
($\sqrt{s}$=1.96TeV)

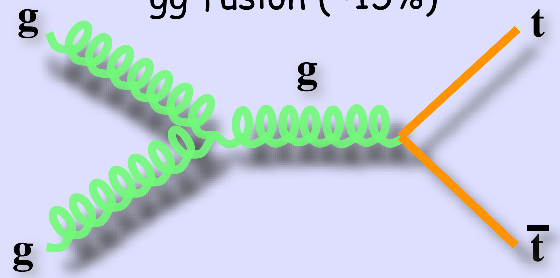
Systematics	Electrons (Run 1b)	Muons (Run 1b)	Common (Run 1b)
Lepton Energy, Scale and Resolution	70 (80)	30 (87)	25
Recoil Scale and Resolution	50 (37)	50 (35)	50
Backgrounds	20 (5)	20 (25)	-
Production and Decay Model	30 (30)	30 (30)	25 (16)
Statistics	45 (65)	50 (100)	-
Total	105 (110)	85 (140)	60 (16)

Total Uncertainty 76 MeV (cf Run 1b 79 MeV)

Top Pair Production & Decay

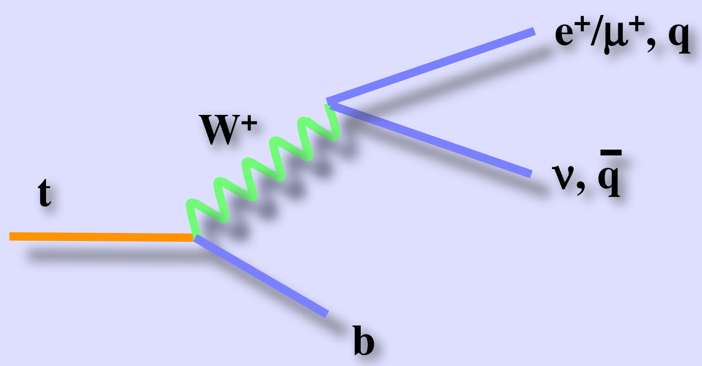
At Tevatron, top is mainly produced in pair via strong interaction

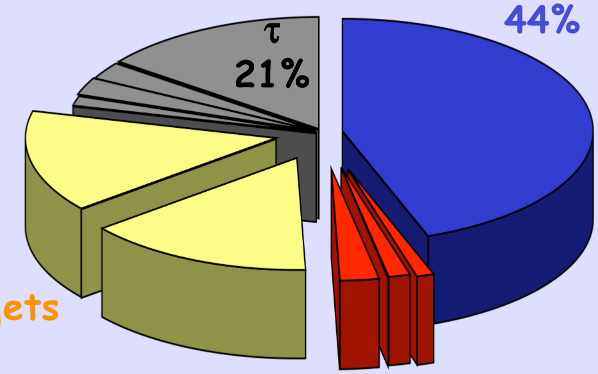




$$\sigma(\bar{p}p \to t\bar{t} \,@\, M_{\mathrm{top}} = 173\ \mathrm{GeV/c^2}) \approx 7.1\ \mathrm{pb}$$

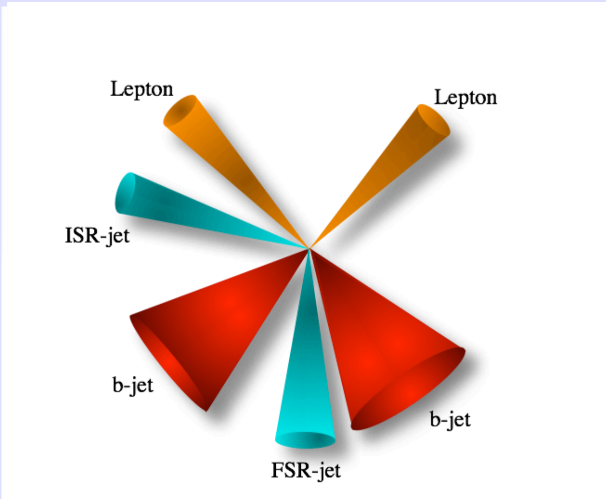
In SM, top decays via the electroweak interaction BR($t \to Wb$)~100%

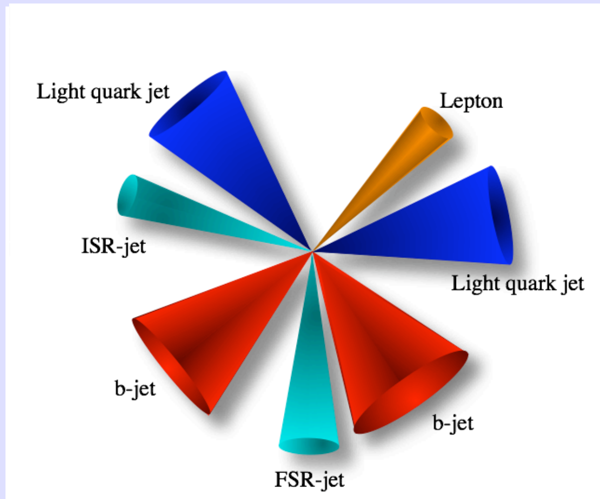


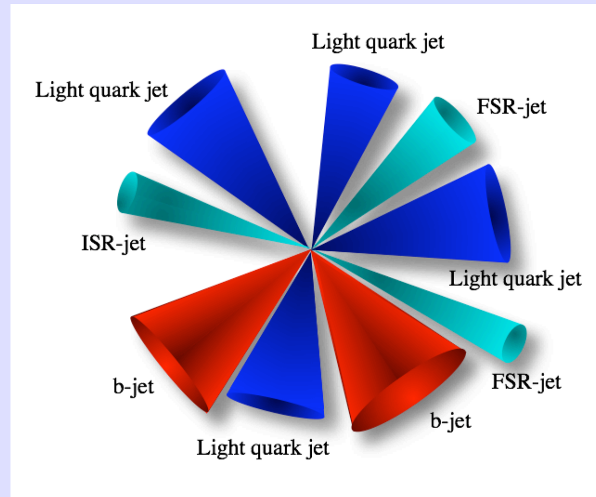


Each channel presents different sensitivity and challenges

Challenges I: Combinatorics







	Dilepton	Lepton+jets	All-hadronic
#Combi	2	12	360
w/b	2	6(1btag) 2 (2btag)	90

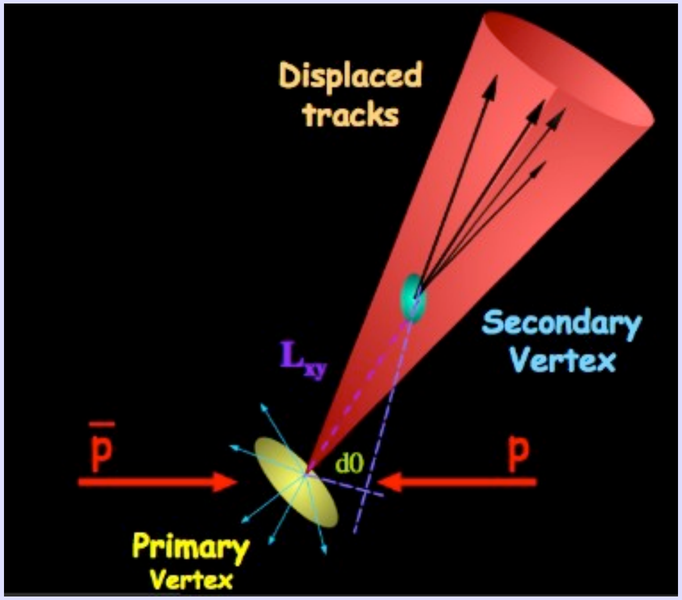
- 2 undetected ν: under-constraint (kinematically complicated to solve M_{top})
- S:B=2:1; 20:1 ≥1 b-tag

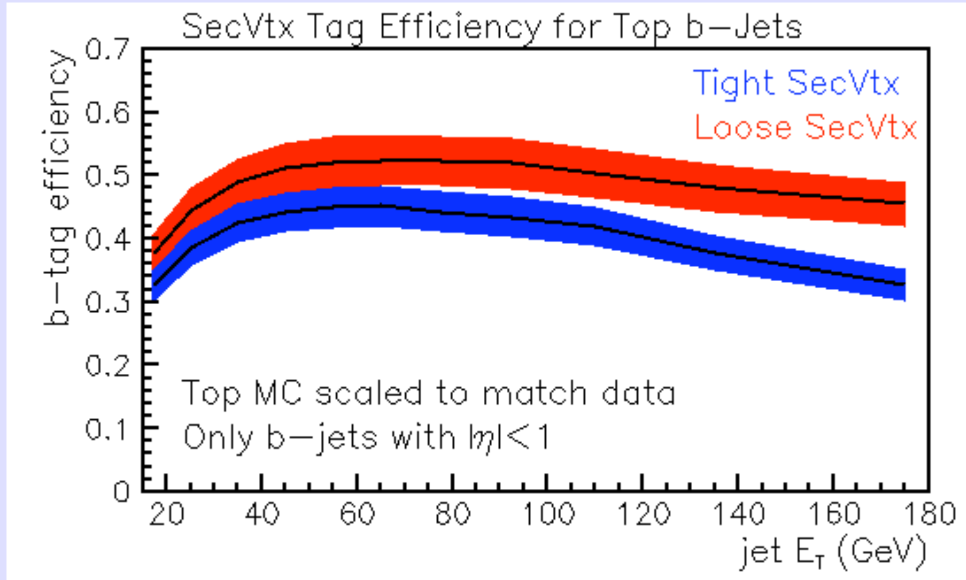
- 1 undetected ν: over-constraint
- S:B=1:4 (11:1 =2 b-tag)
- Golden channel: Most precise M_{top} measurement

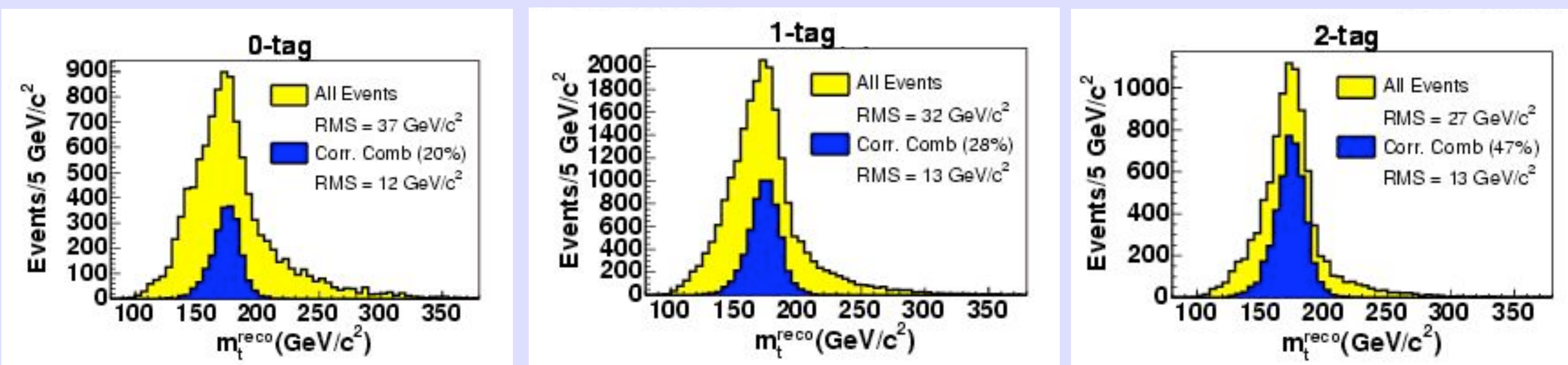
- No ν: over-constraint
- S:B=1:8 =1 b-tag

3 constraints: Two M_W=80.4 GeV/c^2; M_t=M_{tbar}

b-tagging

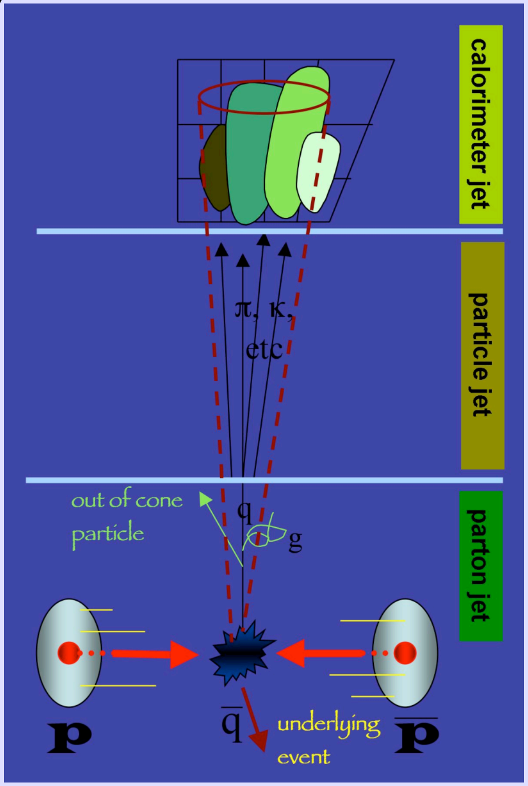






Increases % of right combination & improves resolution

Challenges II: Jet Energy Scale



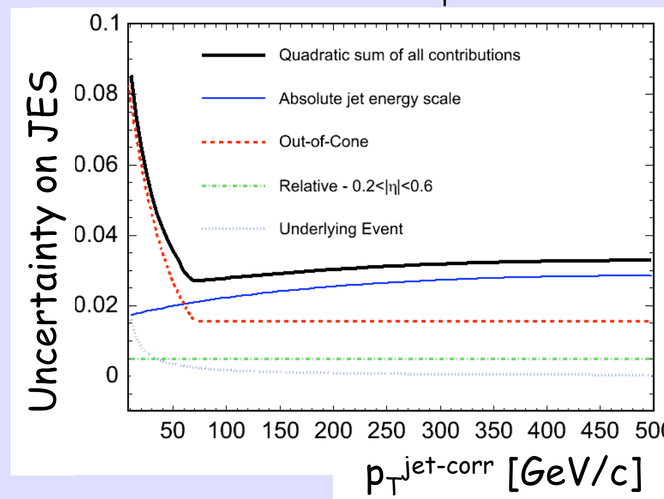
Jet Energy Scale:

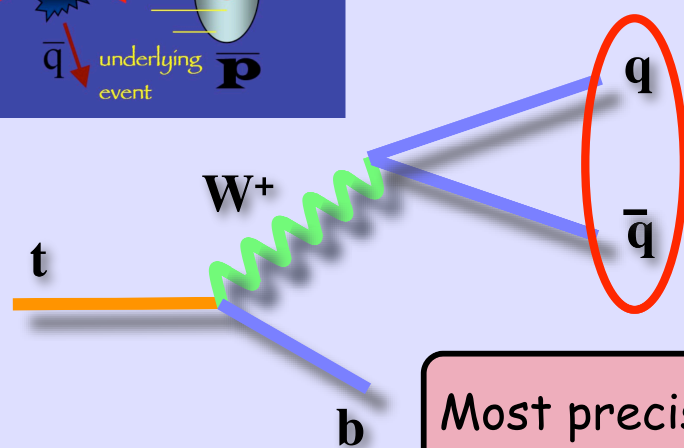
- Determine E of q produced in the hard scatter
- Use MC & data to derive the E scale

Jet Energy Scale Uncertainty:

- Difference between data & MC

~3% JES unct. ⇔ δM_{top} =3 GeV/c^2





New: In-situ jet energy calibration:

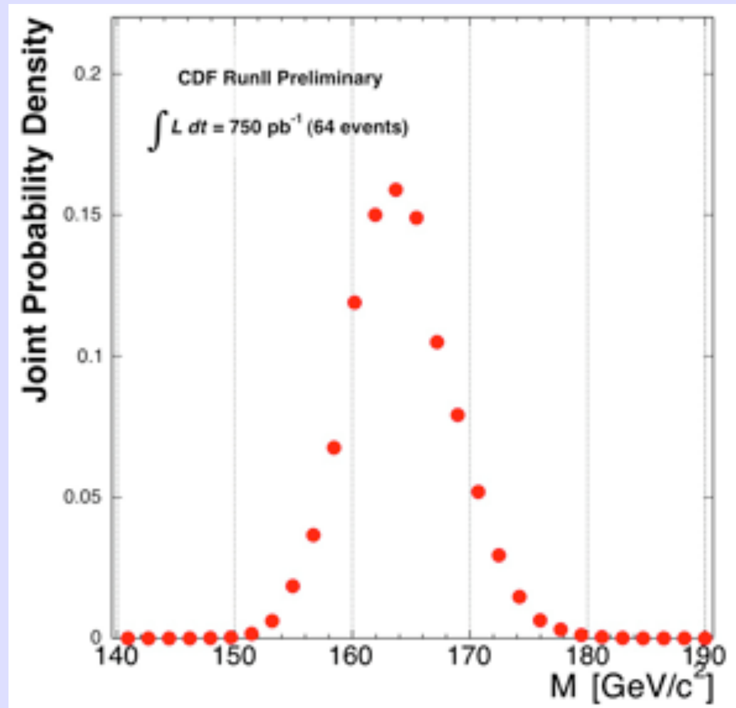
- Constrain the invariant mass of the non b-tagged jets to be M_W
- Use $W \rightarrow jj$ to measure the JES uncertainty
- Scales directly with statistics

Most precise measurements of M_{top} use this technique

M_{top} in Dilepton: Matrix Element method

- Each event gets assign a probability as a function of the top mass
  - Integrate over quantities not directly measured (ν, E_q) using the LO M.E.
    - Assumes lepton and jet angles to be perfectly measured and jets are b's
- Likelihood is a linear combination of the probabilities for signal and background

Source ($750\ pb^{-1}$)	Expecteed Events
DY,WW+jets,fakes	15.7±3.4
EW(WZ,WW,ZZ)	3.6±0.7
Total Backgrounds	19.4±3.4
$t\bar{t}$ (6.1 pb)	36.1±1.2
Data	64



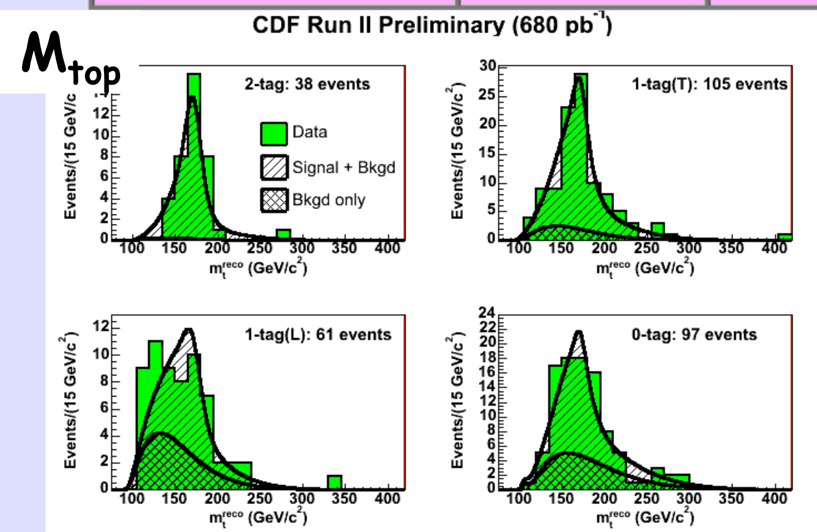
$$M_{top}=164.5\pm4.5(stat.)\pm2.6(JES)\pm1.7(sys.)\ GeV/c^2$$

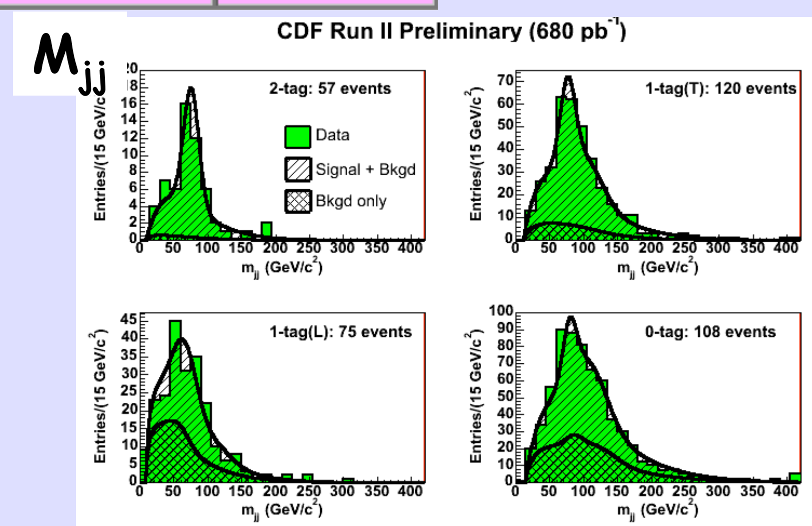
M_{top} in l+jets: Template method

- Select **reconstructed M_{top}** from assignment yielding to lowest χ^2
- Use **templates** of top signal at different mass and background
- Reconstructed M_{top} & M_{jj} (from data) are compared to true M_{top} templates and ΔJES (jet energy uncertainty shift) using an unbinned likelihood

Source (680 pb^{-1})	2 b tags	1 b tag (T)	1 b tag (L)	0 b tag
Expected S:B	~11:1	~4:1	~1:1	~0.6:1
Expected total ($sigma_{tt}$=6.1 pb)	~47	~104	~64	No apriori estimate
Data	57	120	75	108

40% improvement on JES using in-situ calibration

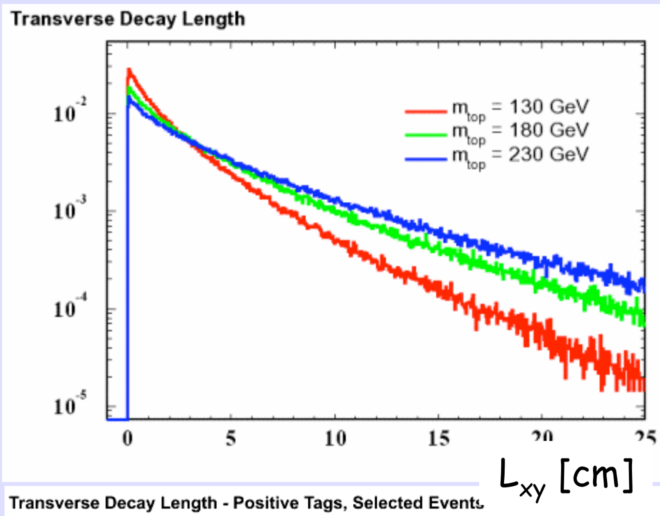


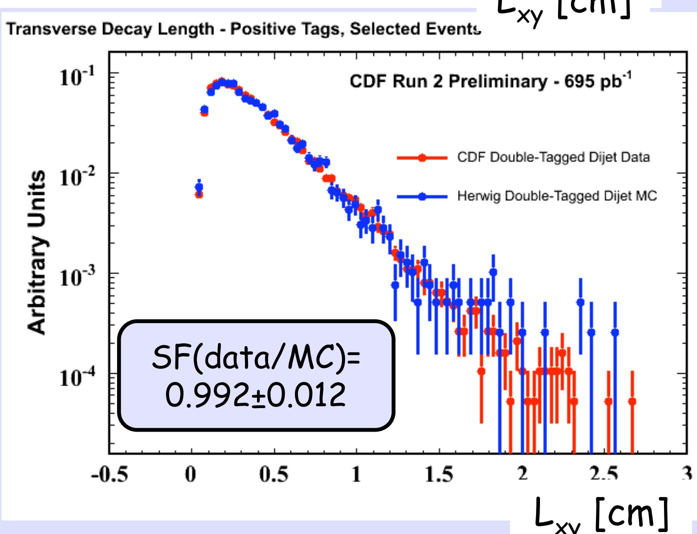


$$M_{top}=173.4\pm2.5(stat.+JES)\pm1.3(sys.)\ GeV/c^2$$

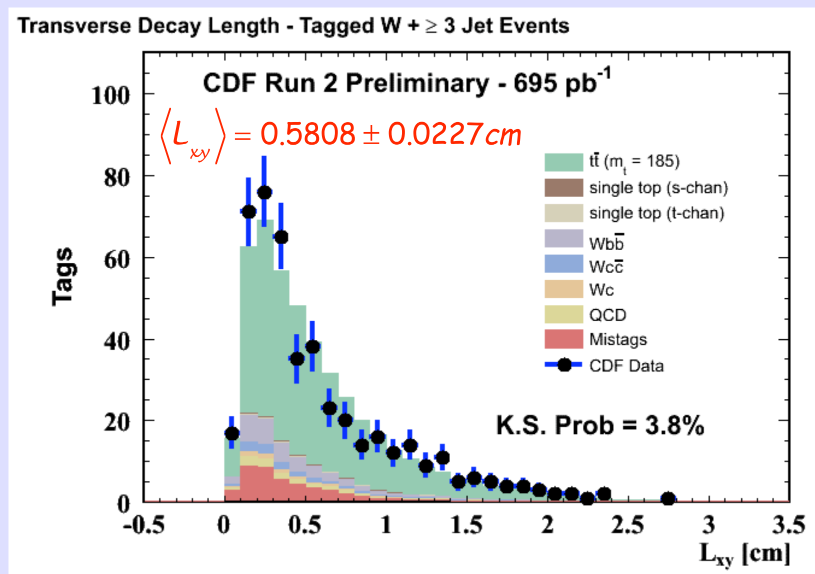
M_{top} l+jets: Average Decay Length method

- B hadron decay length (L_{xy}) $\propto$ b-jet boost $\propto$ M_{top} (PRD 71, 05029)
- Relies on tracking, no JES & uncorrelated with other measurements





(695 pb^{-1})	Expecteed Events
Total Backgrounds	111.6±12.5
Data	375



$$M_{top} = 183.9^{+15.7}_{-13.9}(stat.) \pm 5.6(sys.)\ GeV/c^2$$

M_{top} in all-hadronic: Ideogram method

Kinematic fitter (χ^2) to fit 2 M_{top}

2D likelihood (mass, purity)

Use χ^2 & b-jet information to determine weight

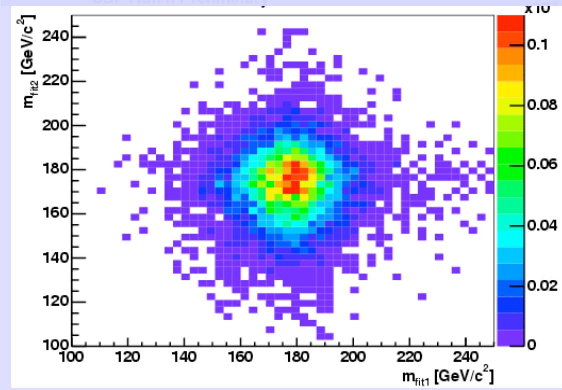
$$L(M_{top},P_s)=\sum_{i=1}^{90} w_i\left[P_s Signal+\left(1-P_s\right)Bkg\right]$$

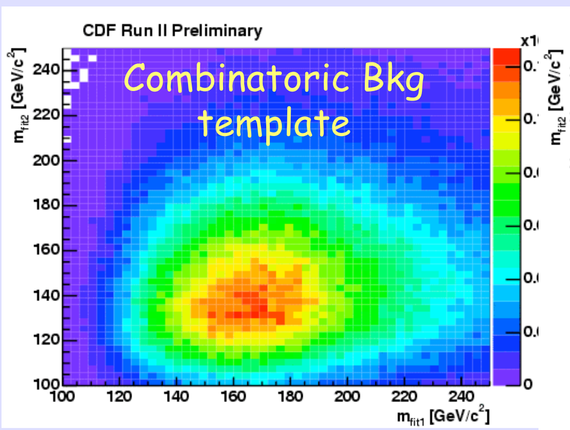
$$Signal\left(m_i^1,m_i^2,\sigma_i^1,\sigma_i^2,M_{top}\right)=p_{match}S_{match}+\left(1-p_{match}\right)S_{comb}$$

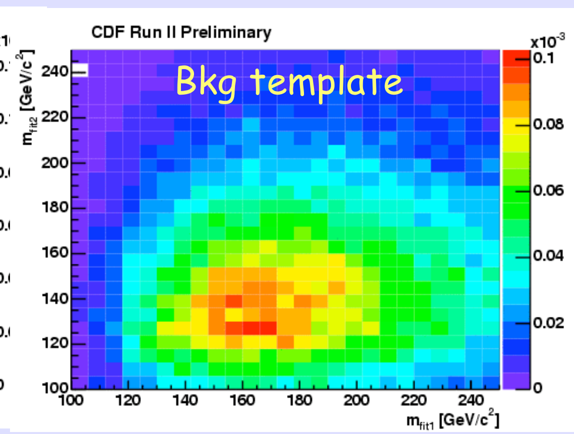
Convolution Breit-Wigner and Gaussian resolution functions

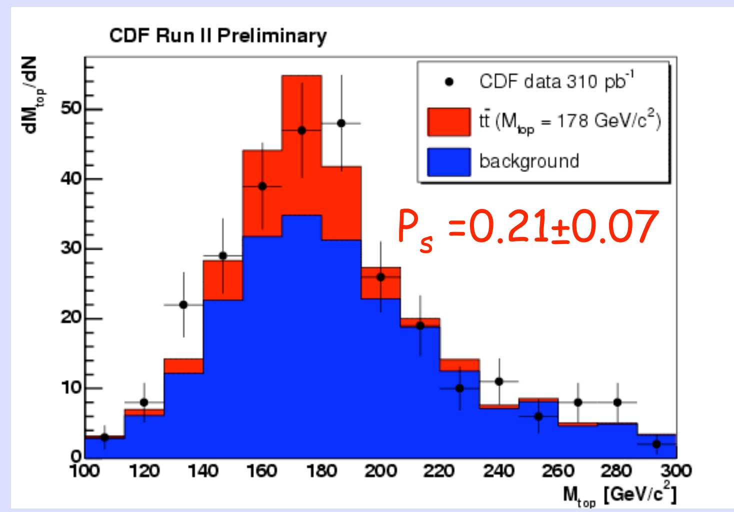
Combinatorial background from MC

e.g Fitted masses for signal MC, right combination



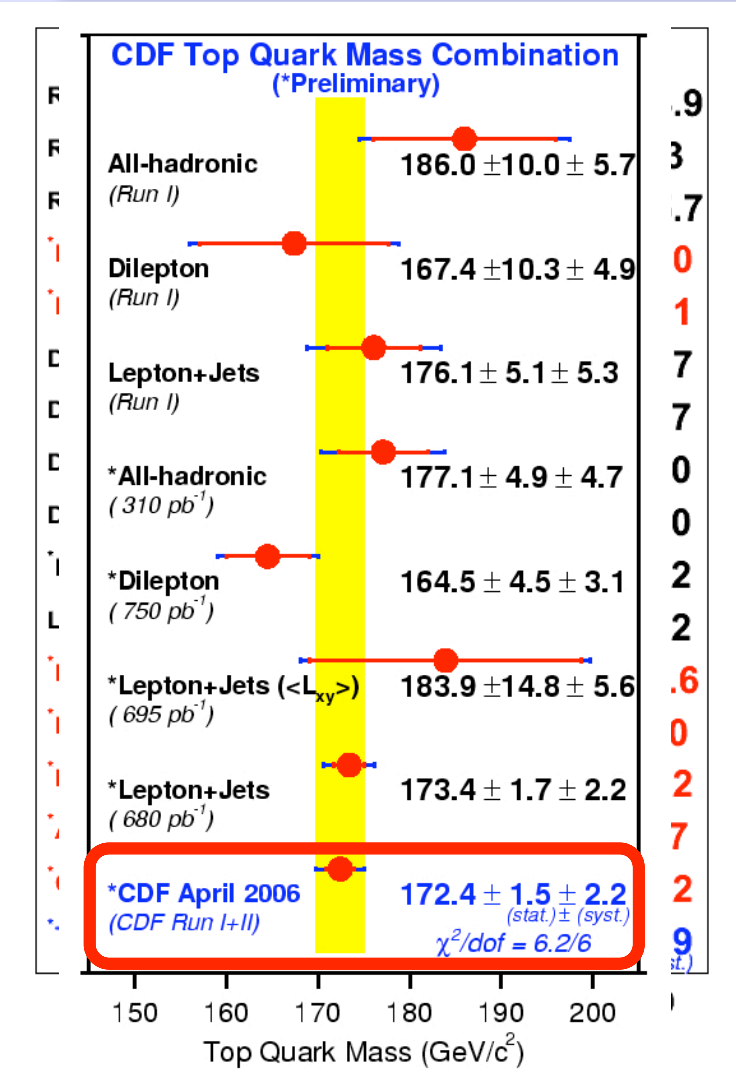






$$M_{top}=177.1\pm4.9(stat.)\pm4.3(JES.)\pm(1.9.)\ GeV/c^2$$

Combining M_{top} Results



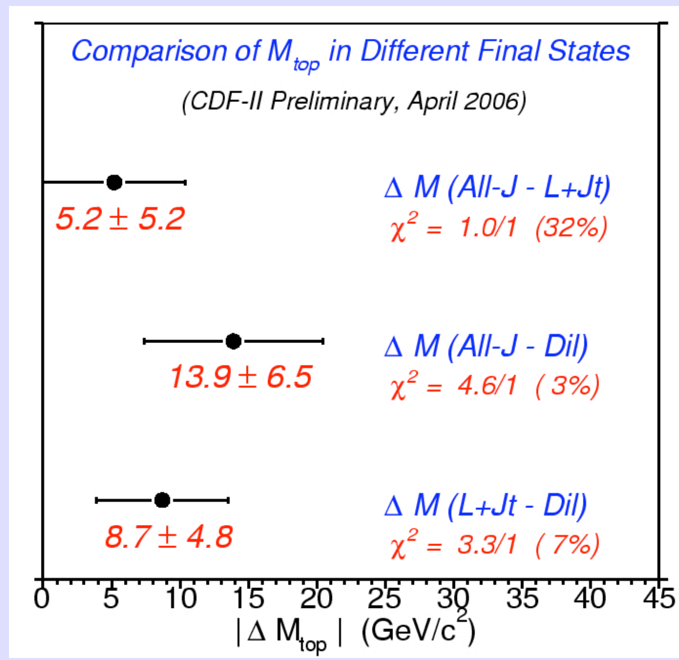
Combine to improve precision

Are the channel consistent ?

M_{top}(dilepton) = 164.8±4.8 GeV/c²
M_{top}(l+jets) = 173.5±2.8 GeV/c²
M_{top}(all-hadronic) = 178.7±5.5 GeV/c²

Any systematic shift ?

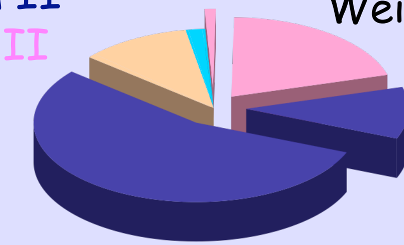
- Missing systematics ?
- Bias due to new physics ?



Implication For Higgs & SUSY

Tevatron Average:
M_{top} = 172.5±2.3GeV/c^2 (1.3%)

CDF Run II
D0 Run II
Weight %



Precision EWK fit assuming SM:

$$M_H = 89^{+42}_{-30}\ GeV/c^2$$

$$M_H < 175\ GeV/c^2 @95\%C.L.$$

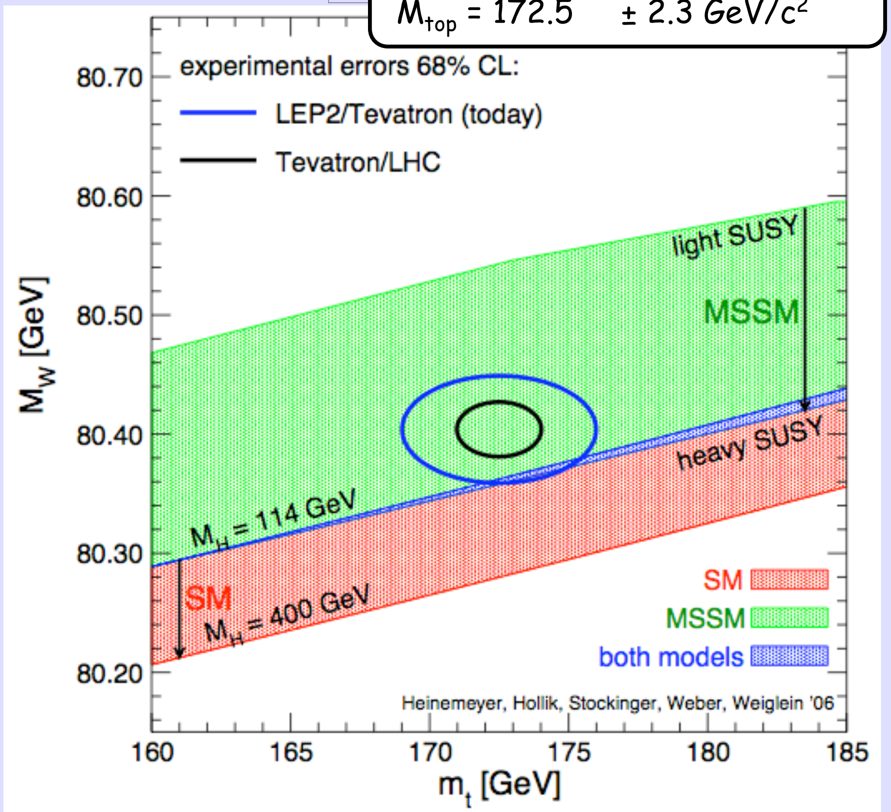
Or (including LEP-2 M_H>114.4 GeV/c^2 @95C.L.)

$$M_H < 207\ GeV/c^2 @95\%C.L.$$

Favors "heavy" SUSY over SM or light SUSY

$$M_H^{MSSM} < 140\ GeV/c^2$$

M_W = 80.404 ± 0.030 GeV/c^2
M_{top} = 172.5 ± 2.3 GeV/c^2

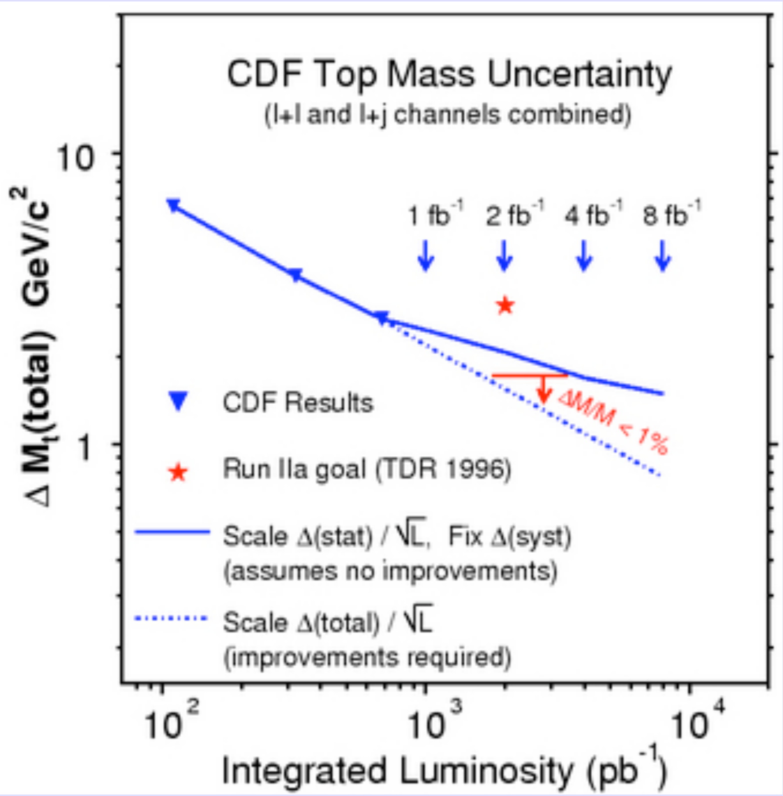


Summary & Prospects

- W Mass
  - Run I combined W mass uncertainty 59 MeV (42 MeV LEP)
  - Run II analysis in advanced stage. Uncertainty **already lower** than Run I.
  - Expectation with 2 fb^{-1}: 40 MeV/experiment, ~30MeV combined

- Top Mass
  - Achieved 1.3% precision with ~0.7fb^{-1} (±2.3GeV/c^2)
    - TDR Tevatron goal with 2fb^{-1} was ±3 GeV/c^2
  - Expectation with full Run II dataset

  < 1.5 GeV/c^2



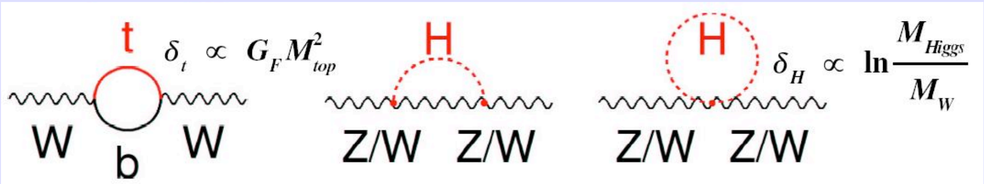
With more precision:

Would the SM continue to hold ?

Where will SUSY fit ?

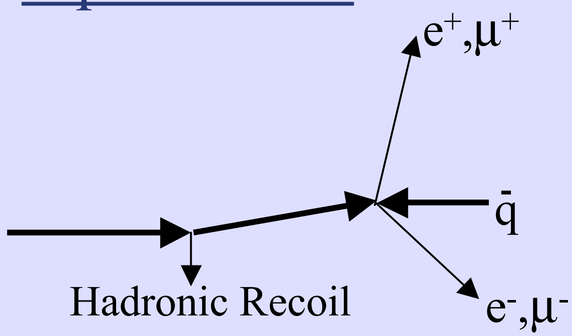
Backup Slides

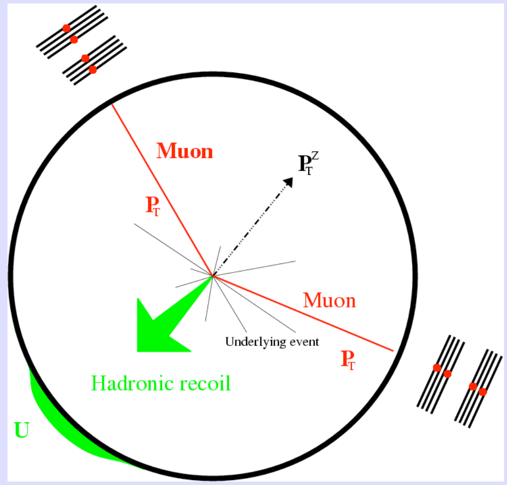
- Large number of measurements from LEP, SLC and Tevatron
  - W mass/width (Tevatron, LEP-2)
  - Top quark mass (Tevatron)
  - Z-pole measurements (LEP, SLD)
    - Z lineshape parameters
    - Polarized leptonic asymmetries
    - Heavy flavor asymmetries and branching fractions
    - Hadronic charge asymmetry
- In the SM, each observable can be calculated/fit in terms of
  - $\Delta\alpha_{had}$, $\alpha_s(M_Z)$, M_Z, M_W, $\sin^2\theta_W$, M_{top}, M_{higgs}, etc…
    - Higgs & top enter as ~1% radiative corrections
  - LEP Electroweak Working Group
    - ZFITTER, TOPAZ0



W/Z event signature

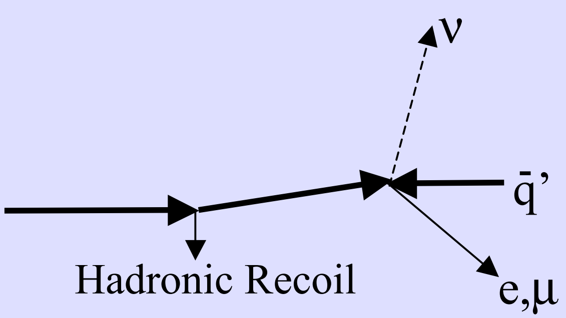
Z production

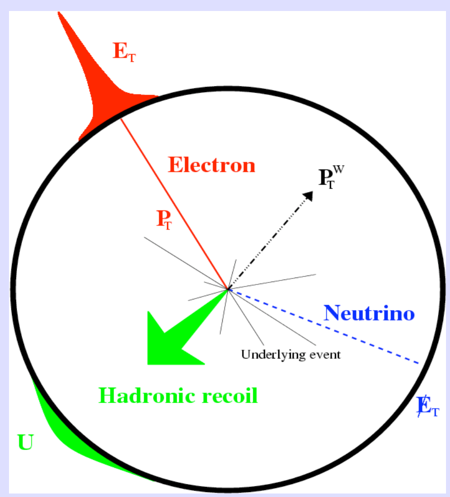




$M_Z = 91.1876 \pm 0.0021$ GeV (LEP)

W production





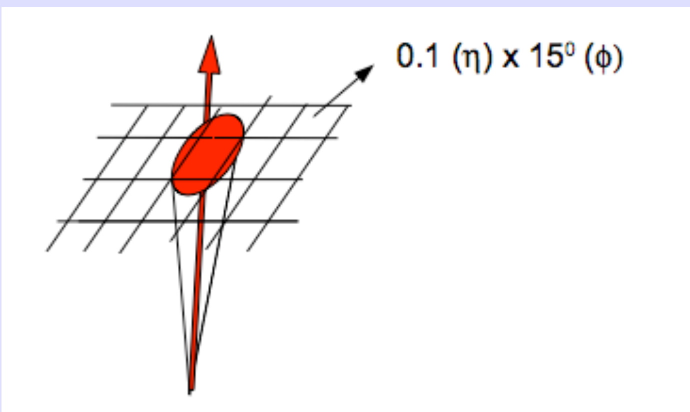
$M_{l\nu} = ?$ ← Can't measure p_Z of ν

$$M_T = \sqrt{2(E_T^l E_T^{miss}[1-\cos(\Delta\phi^{l-miss})])}$$

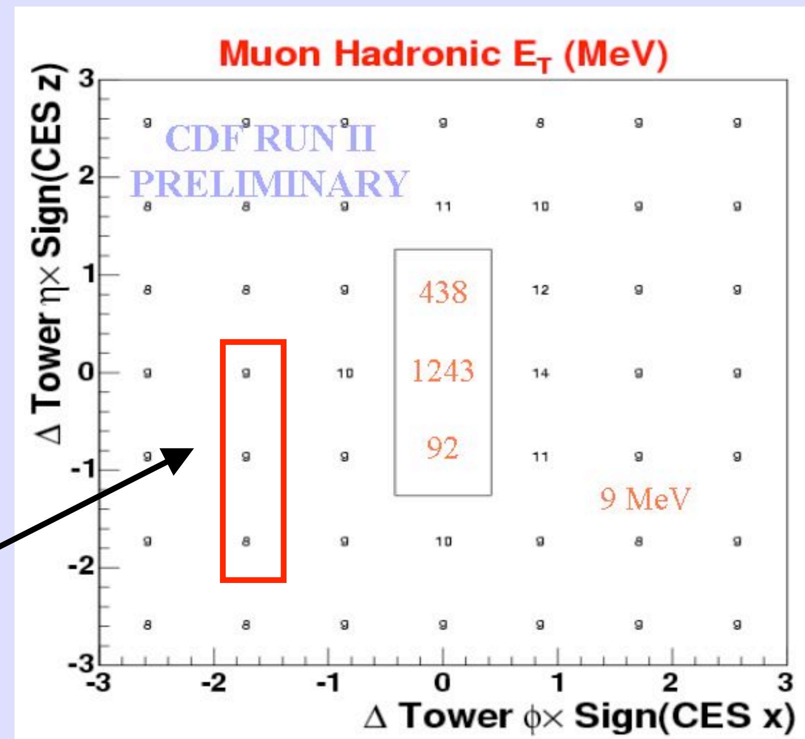
$M_W = 80.425 \pm 0.034$ GeV

W Mass Hadronic Recoil

- Take care of energy in lepton calorimeter towers from underlying event/recoil
  - Look at towers adjacent (in ϕ) to e/μ
- Exploit similar production model of Z events to create ad-hoc model for recoil W events that depends on luminosity

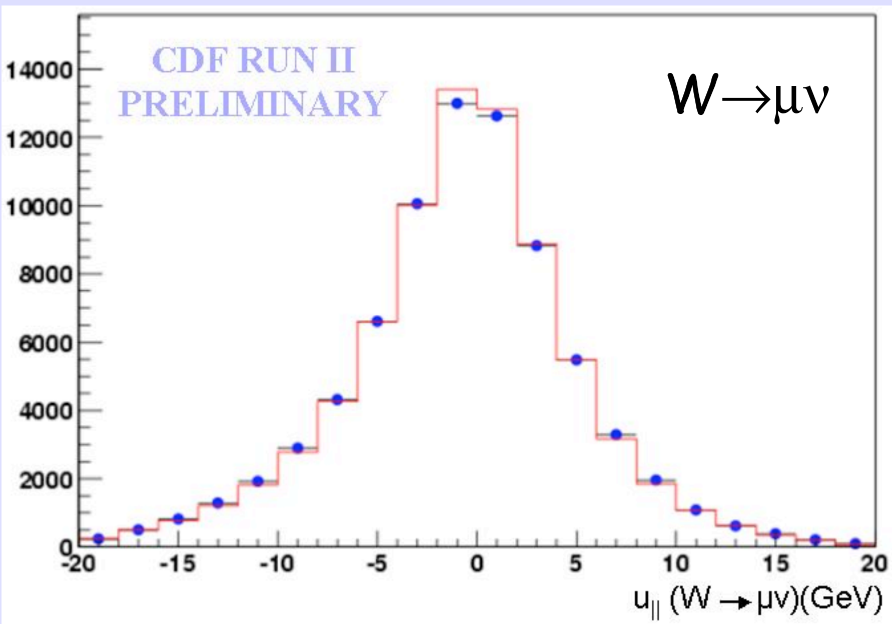


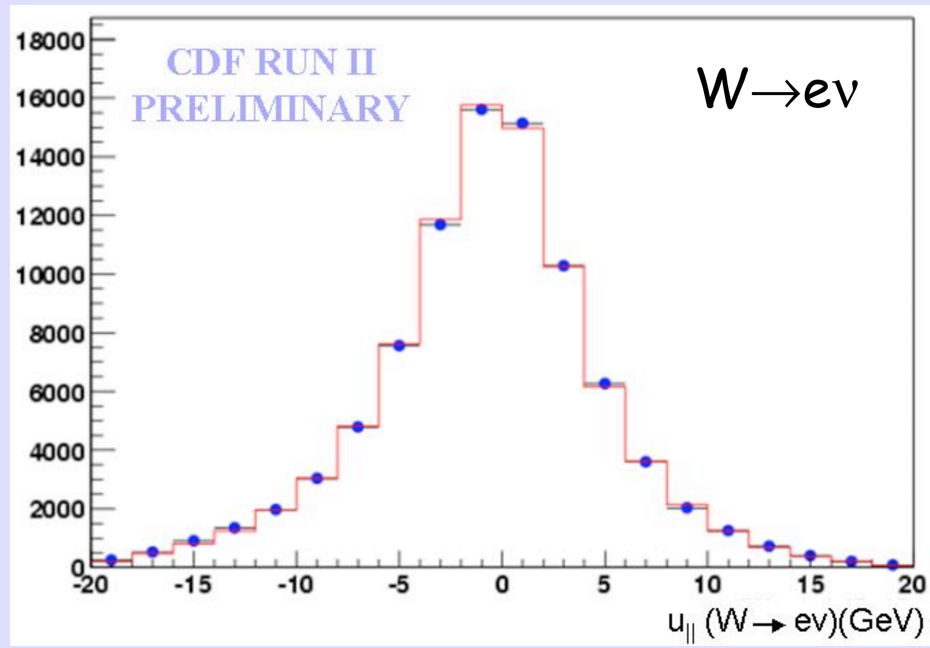
~9 MeV per tower



W Mass: Recoil model

- Take model from fits to Z and min-bias and compare to W events
  - Look at component of U along electron and muon direction: $U_{||}$



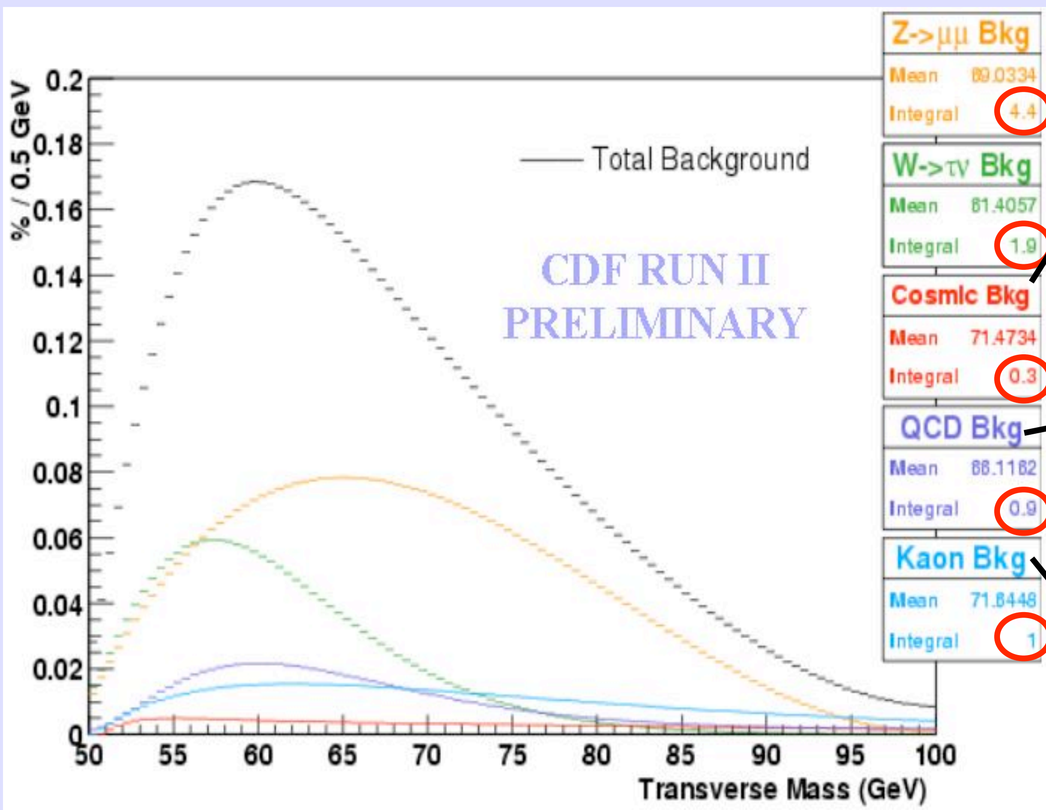


W Mass: Backgrounds

- Z events where one lepton escape detection
- $W^{\pm}\rightarrow\tau^{\pm}\nu;\ \tau^{\pm}\rightarrow e(\mu)\nu\nu$

Estimated from MC

- Other backgrounds are estimated from data by loosening cuts and extrapolation



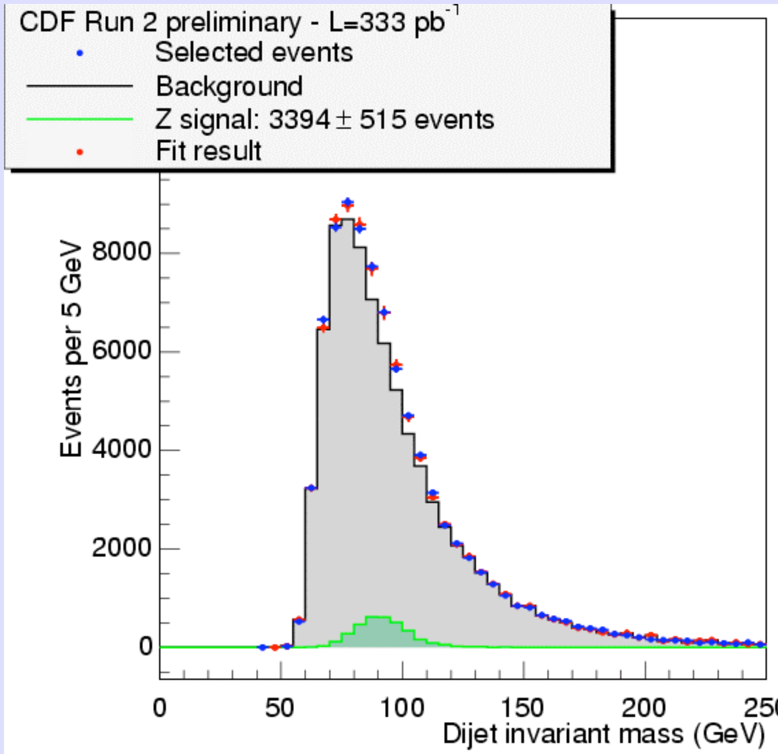
From track hits timing

Look at M_{Et} distribution in events where lepton is not isolated

Decay in COT leads to track mismeasurent & M_{Et} opposite track
Use $\Delta\phi(l, M_{Et})$

Zbbar: b-specific jet E scale

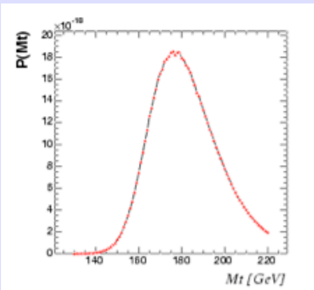
- Challenge 1: Find the events in huge QCD background
  - Use 2 displaced track trigger (SVT). After b-tagging: ~90% bbar
    - Select 2 back to back jets (Et>20 GeV, $|\eta|<1.5$) & no other jet with Et>10GeV
- Challenge 2: Lowest possible cuts on jet Et to obtain a signal far from dijet mass turn-on
  - Without introducing biases & sculpting effects at low dijet masses
- Challenge 3: Obtain reliable dijet mass background shape to fit the data
  - Background shape taken from tagged events in control region.
  - Small fluctuation in background shape can result in large systematic effects in measuring b-jet Energy SF.



M_{top} in Dilepton channel

- Reconstructing Mtop from dilepton events represent a particular challenge:
  - 2 ν from W undetected, only 1 Met measurement: decay assumptions are insufficient to constraint the event
- For each event calculate differential cross-section:

$$P_S\left(x \middle| M_t\right) = \frac{1}{\sigma\left(M_t\right)} \int d\Phi_6 \left|\mathcal{M}_{t\bar{t}}\left(q_i, p_i; M_t\right)\right|^2 \times \prod_{jets} \mathcal{W}\left(p_i, j_i\right) f_{PDF}\left(q_1\right) f_{PDF}\left(q_2\right)$$



Phase space integral over unknow quantities

LO Matrix element

Transfer functions

<u>Only partial information available:</u>
- Fix measured quantities
- Integrate over unknown parton quantities consistent with ttbar production and measured event

qi: 4-momentum of initial partons
pi: 4-momentum of final partons
x: measured event variables

M_{top} in Dilepton channel

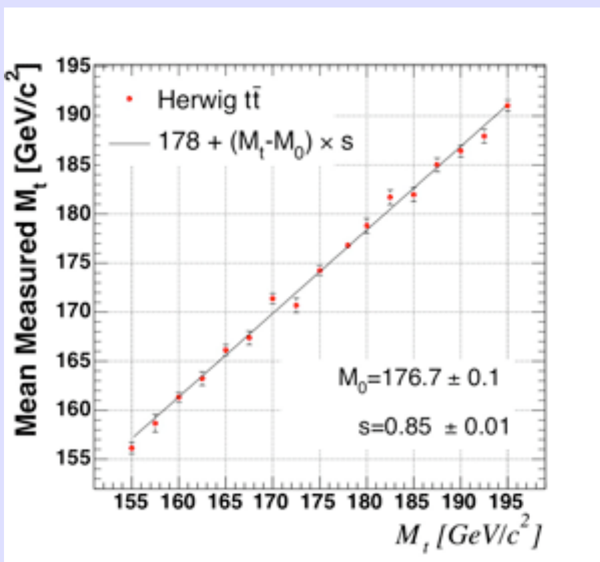
Weighted sum of background and signal probabilities

$$P(x|M_t) = P_s(x|M_t)\,p_s + P_{bg1}(x)\,p_{bg1} + P_{bg2}(x)\,p_{bg2}$$

- Test performance with P.E in MC for generated top masses

Response $\langle M_{meas} \rangle$ is linear.

Incomplete modeling of the background contribution lead to slope (small bias), which is corrected.



$$Pull = \frac{M_{meas} - M_{true}}{\sigma_{meas}}$$

Examining pull width reveal that statistical uncertainty is underestimated.
Due to simplifying assumptions (eg jet from radiation rather than b quarks).
Rescale error by factor 1.49